Edge barrier pinning for a single superconducting vortex

D. Kouzoudis, M. Breitwisch, and D. K. Finnemore
Ames Laboratory, USDOE and Department of Physics, Iowa State University, Ames, Iowa 50011
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Thermal depinning of a single vortex trapped in a superconducting thin film has been measured in order to study the Bean-Livingston surface barrier. There are two forces that bias the motion of the vortex in the natural pinning potential of the film. These are the image force pulling the vortex toward the edge of the film and the Lorentz force of the Meissner currents pushing the vortex toward the center of the film. With zero applied magnetic field, a vortex trapped in a clean, well-defined junction will begin to spontaneously move over large distances of 1 μm or more at a temperature where the reduced order parameter is about $\Delta/\Delta_0=0.2$. When Δ/Δ_0 has been further reduced to $\Delta/\Delta_0=0.15$, the vortex exits the film, giving a vortex-free state below T_c. In zero applied field, the data show that the image force clearly causes a trapped vortex to leave the film. When a perpendicular magnetic field is applied, however, results show that new vortices were nucleated for fields higher than 20 mG. At 20 mG, the Meissner current force was only a few percent of the pinning force and this biasing force causes the vortex to exit the film at a temperature 0.050 K lower than in zero field.
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I. INTRODUCTION

Bean and Livingston[1] recognized very early that there was a fundamental surface barrier to flux entry and flux exit from a superconducting material caused by the competition between two separate forces. First, the boundary condition of zero current normal to the surface can be satisfied by placing an image vortex, of opposite sign, outside the surface. There is thus an attractive force on the vortex towards the surface called the image force. Second, an external magnetic field of the same sign as the field of the vortex induces Meissner currents which provide a Lorentz force pushing the vortex towards the center of the film. The aim of this work is to study both the image and Meissner forces for a thin film that has just one vortex in the film.

In zero applied field, each vortex in a superconducting thin film has an array of image vortices that provides a force and a potential tending to move the vortex out of a thin film, the potential being sketched by the dashed line of Fig. 1(a). With a magnetic field applied perpendicular to the film there is a second force pushing the vortex toward the center of the film caused by the screening Meissner currents. Adding the two forces gives a potential barrier that tends to hold the vortex in the middle of the film[2] as shown by the solid line of Fig. 1(a). Hence there is a barrier potential for both entrance and exit of the vortex. Conversely, with an applied perpendicular magnetic field of opposite sign of the field of the vortex, the image force and Lorentz force add constructively to push the vortex towards the edge of the film.

In a real material, of course, there also are imperfections in the thin film that give a spatial variation in the potential energy of any vortex in the film. Hence, a study of the image force and the Lorentz force from the Meissner current must be carried out in the presence of a background of these pinning potentials. The relative strengths of these pinning potentials and the Lorentz and image forces become important.

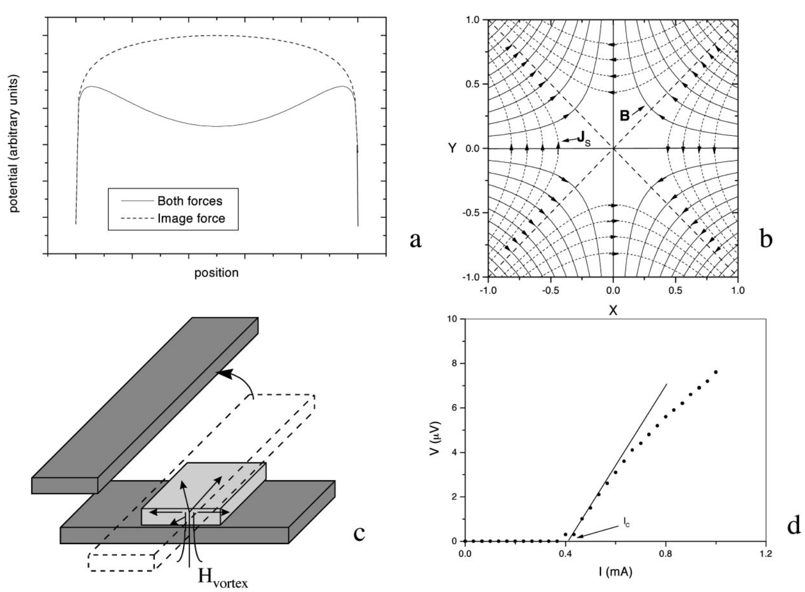

FIG. 1. (a) Potential of a vortex in a thin film created by the image force only (dashed line) and by both the image force and a screening current caused by $B_z\sim\phi_0/W^2$, (b) sketch of magnetic field lines inside the junction (solid) and induced current in the bottom superconductor (dashed line) caused by B_z, (c) sketch of cross-strip junction, and (d) V-I characteristics for SNIS junction.

The zero-field case for one vortex trapped in a thin film has been studied in some detail for an exiting vortex for both Pb (Ref. 3) and Nb (Ref. 4) thin films. In these films, the goal was to make the applied magnetic field less than 10^{-7} T and study the thermal depinning and motion of the vortex in the presence of only the image force. To carry out the experiment, a vortex was nucleated at the edge of the film and moved to some location, usually near the middle of the film. By raising the temperature toward the superconducting transition temperature T_c, where the order parameter Δ is suppressed, the gradient of the pair potential near the pinning site is reduced and the vortex will spontaneously depin and move to some other site. Data for both Pb (Ref. 3) and Nb (Ref. 4) show that the vortex thermally depins and begins to move around the thin film when the order parameter is reduced to $\Delta/\Delta_0 \sim 0.20$ and the vortex exits the film when $\Delta/\Delta_0 \sim 0.15$. Here Δ_0 is the value of Δ at $T=0$. In both the pure Pb and pure Nb cases, the pinning was weak and the vortex typically took four to six hops before it exited the film. In both of these earlier cases, the image force would overcome the pinning potentials and pull the vortex out of the film for temperatures high enough to give $\Delta/\Delta_0 \sim 0.15$.

To conduct these experiments, it is necessary to determine the location of the vortex and to follow the displacement as it hops around a thin film. This is done by placing a Josephson junction over the thin film in a cross strip geometry and measuring the Fraunhofer-like interference pattern for the critical current vs magnetic field applied parallel to the junction. The parallel field modulates the relative phase between the two superconducting films to produce a diffraction pattern. There is a direct connection between the location of the vortex and the shape of the interference pattern so that the interference pattern can be used as a ‘‘fingerprint’’ to specify the location of the vortex.[5]

In these experiments, there is a special interest in fields applied perpendicular to the junction. In this geometry there is a theory, well verified by experiment, that predicts the current and magnetic field pattern within the junction in the presence of a field perpendicular to the plane of the junction as shown in Fig. 1(b).[5] With a magnetic field perpendicular to the junction B_z, the magnetic field lines cross the corners of the junction and the induced currents flow in arcs along each of the four edges as shown in Fig. 1(b). Currents circulate to cancel the applied field, and the pattern is more complicated than for a cylindrical specimen in an external field. The force on a vortex is given by $\vec{J}_s \times \vec{\phi}_0/c$ where $\vec{J}_s$ is the supercurrent at the position of the vortex and the direction of $\vec{\phi}_0$ is given by the field direction of the vortex. For a vortex in the bottom film with field parallel to the external field the force lines are the same as the magnetic field lines shown in Fig. 1(b). The force is away from the center of the junction in the y direction and away from the edge of the film in the x direction. Reversing the external field reverses the direction of the force on the vortex. The Meissner screening currents will push a vortex out of the junction region regardless of the direction of the applied magnetic field. Our experiment cannot distinguish between the vortex leaving the junction region by exiting the film altogether or moving along the film outside the junction region.

The purpose of this work is to study the motion of a single vortex as it thermally depins and responds to both the image force and the Lorentz force caused by currents induced to shield B_z. The spatial variations in the flux pinning potential will vary from film to film, and we want to study the depinning behavior for several cases.

II. EXPERIMENTAL TECHNIQUE

Cross-strip superconductor-normal-insulator-superconductor (SNIS) Josephson junctions were prepared in a three-gun sputtering system. Typically, the chamber is pumped to about 4×10^{-8} Torr and backfilled with the desired pressure of Ar. A load-lock chamber was available so that the substrate could be lifted to change masks without breaking the vacuum. First, a strip of Nb was sputtered onto the Si substrate about 80 μm wide and 400 nm thick for the bottom Nb film. A Ag strip about 250 nm thick was deposited over the bottom Nb strip to provide a normal metal barrier and to protect the bottom strip during the Al oxidation step. Before depositing an Al layer, the substrate was lifted about 1 mm above the mask so that the Al strip would be substantially wider than the Nb and Ag bottom strips. The Al was sputter deposited over the Ag to a thickness of about 350 nm. At this point Ag pads for electrical contacts were sputtered onto the Si substrate and the edges of the Al layer to make good contact with the Al before it was oxidized. To oxidize the Al, a negative voltage of 512 V was applied to an Al ring below the substrate and about 80 mTorr of oxygen was admitted to create a glow discharge for 1 h. After the oxidation process, the pressure was reduced below 10^{-8} Torr and the Ar was brought to about 20 mTorr. A top Nb strip that was 80 μm wide, 400 nm thick, and oriented perpendicular to the bottom strip was then deposited.

The junctions were mounted in a cryostat having four layers of Co-Netic shield material to reduce the ambient field to about 10^{-7} T or 1 mG as measured by a flux gate magnetometer. The sample was mounted with the bottom Nb film along the vertical or y axis. The top film was along the x axis and the magnetic fields to produce the Lorentz force were along the z axis. Time, temperature, and magnetic field sequences in association with the usual Fraunhofer interference patterns were taken with a data acquisition software to control the experiment. In all cases, the fields and currents were gradually ramped to the desired values over a few second intervals to prevent induced voltages from suddenly changing fields. In other respects the experiments were similar to previous work. Diffraction patterns to determine the location of the vortex are all taken in the small junction limit where the Josephson penetration depth was larger than the junction so that the currents density would be uniform in zero applied field. Usually this was with the field along the vertical or y axis at 7.850 K where the critical current at $B_y=0$, I_{00}, is 1 mA. With this value of I_c, the Josephson penetration depth is greater than 100 μm, assuring that the Josephson current is essentially uniform across the junction and that the measurements are in the small junction limit. We report two junctions with rather different flux pinning characteristics in some detail here.

III. RESULTS AND DISCUSSION

A. Sample 1

For junction 1, the normal state resistivity at 10 K is $\sim 4\ \mu\Omega$ cm for both films. Defining T_c as the temperature

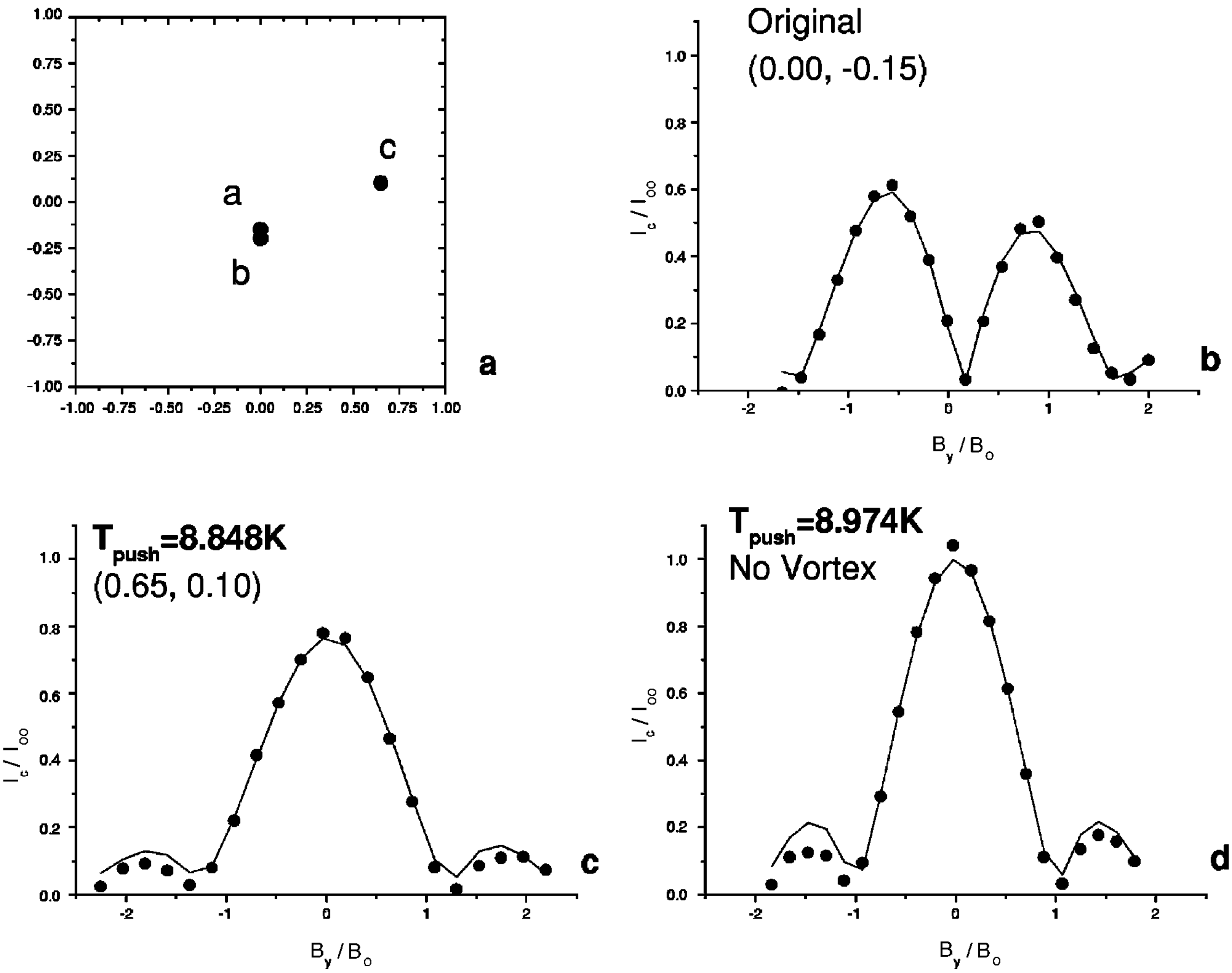

FIG. 2. For sample 1, (a) shows a sketch of the locations of vortices. Diffraction patterns for the vortex at (b) (0.00, -0.15), (c) (0.65, 0.10), and (d) no vortex. The solid line represents the theoretical fit for the given location.

where the resistance of the entire film goes to zero, the T_c of the top film is 9.31 K and the T_c of the bottom film is 9.06 K. In the region of the junction, the T_c may be slightly higher. The oxidation of the Al always seems to degrade the T_c of bottom film, presumably because some oxygen gets into the bottom layer of Nb even though it is coated with both Ag and Al. Also, since the entire bottom strip is covered with Ag, T_c could be lowered from the proximity effect.

For SNIS junctions, the voltage-current curves do not follow a resistively shunted junction (RSJ) model, but rather rise roughly linearly from zero as described in some detail previously.[6] At temperatures below 8.9 K, the voltage-current (V-I) curves rise approximately linearly for zero voltage and then round over into the high current resistance for the junction as expected for SNIS junctions. If the critical current (I_c) is defined by the intercept of the steepest slope region with the $V=0$ axis, then $I_c \sim (1-T/T_c)^{3/2}$ from 6.9 to 8.9 K. Above 8.9 K, there are traces of a supercurrent through the Josephson junction all the way up to 9.1 K. Above 8.9 K, however, the junction resistance rises rapidly as discussed by Hsiang and Clarke.[7] In this regime, the order parameter has a strong space dependence within the thin film and characteristic decay lengths comparable to the film thickness.

To nucleate a vortex in the bottom film, the junction was warmed to 9.5 K, well above T_c of both films. The temperature was then dropped to 9.10 K, a temperature where the top film was fully superconducting and the bottom film was still normal. At this temperature the top film acts like a ground plane. A current of 250 μA then was applied in the bottom film and the heater was turned off, dropping the temperature to 4.2 K. Usually this would nucleate a vortex at (0.00, -0.15) where the x and y coordinates are measured from the center of the junction in units of $W/2$ where W is the width of the film. The diffraction pattern for this location is given in Fig. 2(b) and a sketch of the location is marked a in Fig. 2(a). As reported previously, a vortex near the center of the junction gives a two-peak structure with a minimum in I_c at $B_y=0$.[5]

To conduct a zero-field depinning run, the sample was warmed to some desired temperature, held for 10 s, and then ramped back to 7.850 K where a diffraction pattern was taken to see if the vortex had moved. If there was no motion, the sample was ramped to some slightly higher temperature with no overshoot, held as before, and ramped back to 7.850 K for the next diffraction pattern. Taking temperature intervals of 0.003 K for successive cycles, it was found that the vortex first moved at 8.754 K from (0.00, -0.15) to (0.00,

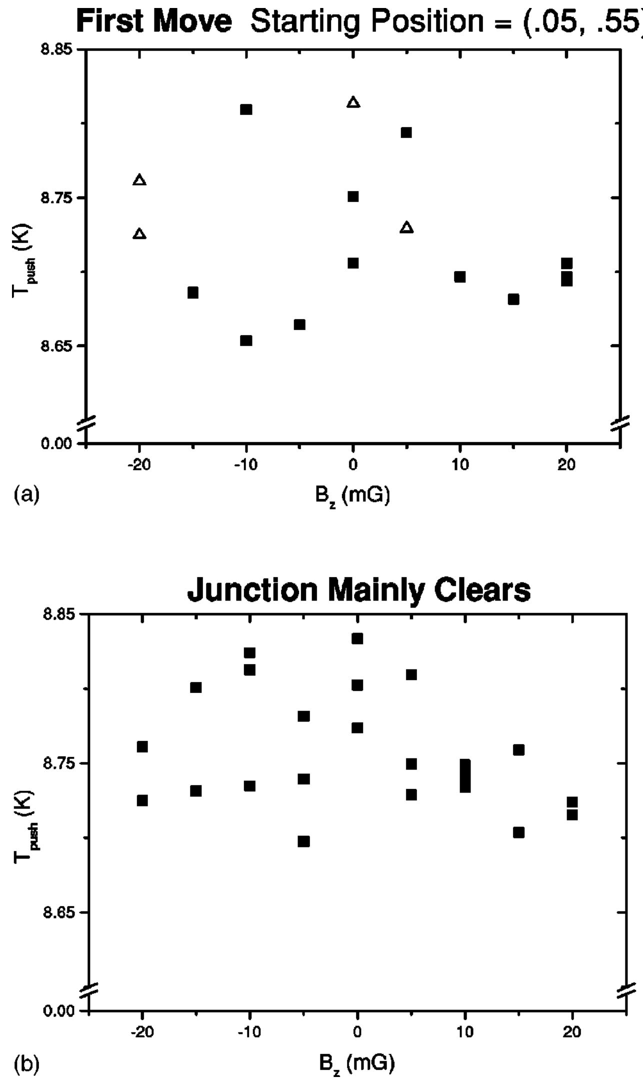

FIG. 3. For sample 1, plot of temperature where (a) the vortex first moves and (b) the vortex exits the junction as a function of B_z for several runs.

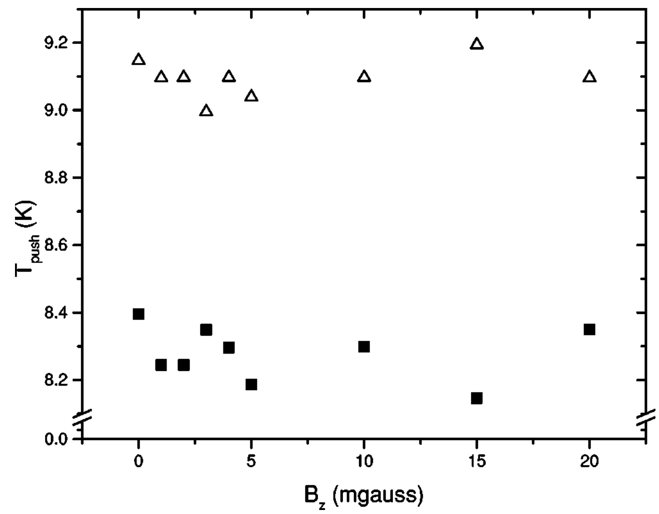

FIG. 4. For sample 2, plot showing the temperature where the vortex first move a small distance (solid squares) and the temperature where the vortex moves to the edge of the junction (open triangles).

-0.20) with a diffraction pattern only slightly different from that shown in Fig. 2(b). This is a distance of about 2.0 μm along the negative y axis from point a to point b as shown in Fig. 2(a) and represents about the smallest jump that we can reliably detect. The next jump occurred at 8.848 K from $(0.00, -0.20)$ to $(0.65, 0.10)$ indicated in Fig. 2(c). On the third jump that occurred at 8.974 K, the vortex exited the junction to give the circles in Fig. 2(d). This is a typical sequence in which a vortex jumps a few times under the influence of the image force and then exits the sample.

A systematic study was then made of the temperature at which the vortex first moves as a function of B_z, a field applied perpendicular to the plane of the junction. For these data, the temperature interval between successive depin points is 3 mK and all of these measurements started with the vortex at (0.05, 0.55). On some occasions the first jump of the vortex clears the junction in one step as shown by the triangles in Fig. 3(a). Most of the time, however, the first jump is from (0.05, 0.55) to $(0.75, -0.75)$ as shown by the solid squares in Fig. 3(a). The reason for the scatter in the data has not been established, but the most likely explanation is that, even though the starting location of the vortex is nominally (0.05, 0.55), there are several pinning sites close to this point so that the starting configuration is slightly different each time. Reversing B_z reverses the direction of the Meissner force but still pushes the vortex out of the junction region. The data for $+20$ and -20 mG are essentially the same. Data were not taken at higher B_z because other vortices are usually nucleated.

A plot of the temperature where the vortex exits the junction is shown in Fig. 3(b). At both $+20$ and -20 mG, the vortex exits the junction at about 50 mK lower temperature than for the zero-field case. There is a lot of scatter in the data, but a decrease in the upper bound of the temperature at which the vortex exits the junction as the magnitude of B_z is increased is visible. If the Lorentz force from the Meissner screening currents of the applied B_z were comparable to the pinning forces, we would expect a lower depinning temperature for fields of both the same and opposite signs as the field of the vortex. We do not know the sign of the field of the vortex. Since the vortices had the same initial location and were nucleated with the same procedure, however, each vortex most probably had the same sign. The fact that the temperature at which the vortex exits the junction decreases only slightly as the magnitude of the applied magnetic field increases tells us that the strength of the pinning forces are much larger than the Lorentz force from the applied magnetic field up to 20 mG. If the current densities expected for a cross-strip junction in a perpendicular field of 20 mG are calculated for location (0.05, 0.55), as in Miller *et al.*,[5] the pinning force from $F=(J\times\Phi_0)/c$ is about 7×10^{-15} N. This is about 10% of the typical pinning forces in this temperature range, so there was some hope of seeing the effect. As the temperature is increased towards the temperature at which the vortex would have thermally depinned with no applied magnetic field, the vortex is helped off the pinning site by the Lorentz force but it is not easily seen in these data.

B. Sample 2

Sample 2 differs from sample 1 in that it is more difficult to clear the junction of vortices for this sample. A trapped

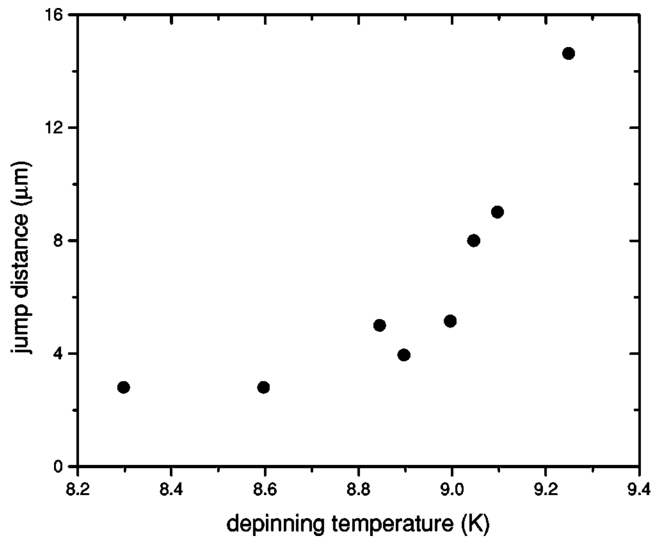

FIG. 5. For sample 2, distance of jump vs depinning temperature.

vortex tended to remain trapped near the edge of the junction essentially up to T_c. In addition, there was more difficulty trapping just one vortex. More than half the time, cooling through T_c with a current in the bottom film resulted in the trapping of multiple vortices. After three to six attempts, however, a vortex would be trapped near the center of the junction. When a thermal depinning run was initiated, the vortex normally would begin to take small steps of about 2 μm length at about 8.3 K where the normalized order parameter is $\Delta/\Delta_0 \sim 0.5$. For this analysis it is assumed that each change in diffraction pattern arises from the motion of one vortex. Another interpretation is that the central vortex remains fixed and vortices near the edge move, resulting in small changes in the diffraction pattern. At ~ 8.8 K, where $\Delta/\Delta_0 \sim 0.25$, the vortex would begin to take large steps of $\sim 16\,\mu$m length. After taking a large step there might be many small steps again before jumping toward the edge. In Fig. 4, we plot the temperature where the vortex begins to move in small steps (solid squares) and the temperature where a pattern close to a Fraunhofer pattern is recovered, indicating an exit of the vortex from the film (open triangles). For this film, the diffraction pattern indicates a vortex near the edge of the film all the way to T_c.

To describe the motion in a bit more detail, we plot the length of jump vs depinning temperature as shown in Fig. 5. Consistently for all fields up to 20 mG, the vortex begins to take 8 μm steps between 8.8 and 9.0 K. The main result is that these changes are independent of B_z up to 20 mG.

IV. CONCLUSIONS

For clean Josephson junctions that show excellent Fraunhofer patterns for the vortex-free case, and for which it is easy to trap a single vortex, a single vortex will thermally depin when $\Delta/\Delta_0 \sim 0.2$, and the vortex will exit the junction when $\Delta/\Delta_0 \sim 0.15$. This confirms earlier studies with both Pb (Ref. 3) and Nb (Ref. 4). The depinning and motion of the vortex is governed by the flux pinning landscape of the film and eventually either the image force of the vortex or some free energy associated with the Meissner effect causes the vortex to leave the film before the sample reaches T_c.

When a magnetic field is applied perpendicular to the film Meissner screening currents are induced, providing an additional Lorentz force pushing the vortex. For the films studied here, new vortices were nucleated when these perpendicular fields exceeded 20 mG so this limited the range of Meissner forces that could be studied. At 20 mG, the Meissner force depends on the location of the vortex in the junction, but typically this force is only a few percent of the force from the pinning potentials in the film at the temperatures where the observation could be made. Hence, there is only a small effect of this screening current on the motion of the vortex. For the best film, this few percent bias from the screening current causes the exit temperature for the vortex to be 0.050 K lower at 20 mG than the zero-field case as shown in Fig. 3(b).

For the second film, which we believe has more irregularities, it is more difficult to trap just a single vortex in the junction. For these films, there is a tendency to nucleate multiple vortices and it is more difficult to sweep the vortex out of the film. Typically, the vortices in the junction will begin to move in such a way as to produce small changes in the diffraction pattern at 8.3 K and then begin to move in larger steps at 8.8 K where $\Delta/\Delta_0 \sim 0.2$. For these films, the temperature must be raised essentially to T_c before the vortex will clear the edge of the film regardless of an applied perpendicular magnetic field.

ACKNOWLEDGMENTS

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